Experiments on a New Cathode Dark Space in Helium and Hydrogen.

By F. W. Aston, A.I.C., Research Scholar, the University of Birmingham.

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[Plate 1.]

In a paper recently read before this Society,* the author described some experiments on the length of the Crookes dark space under varying conditions in different gases. While the gas hydrogen was under this investigation, a slight inequality of light was noticed very close to the cathode, which, under the prevailing conditions, was not definite enough to warrant further attention at the time. When, however, helium was introduced into the apparatus, this phenomenon became strikingly clear, showing itself to be a hitherto undescribed dark space very close against the cathode and inside the Crookes dark space, possessing very different properties from the latter. By the time the measurements of the Crookes dark space in helium were completed, the behaviour of the new dark space had suggested a simple explanation, which led to a series of experiments, of which this paper is a description.

Apparatus.—The preliminary observations of the new dark space were made in the "guard ring cathode" discharge tube already described,† but when it was realised that an accurate knowledge of the current density was not required, this was replaced by a smaller cylindrical tube, 8 cm. in diameter, with more uniform walls and plane aluminium cathode and anode. With this exception, the apparatus was entirely as described in the previous paper.

Measurement of the Length of the New Dark Space.—As this is exceedingly small (its greatest length under measurable conditions is about 0·1 cm.), its measurement was found to be a matter of considerable difficulty; any attempt at magnification by a telescope was, as with the Crookes dark space, worse than useless, and, after trying several methods of micrometry, the plain sighter used for the latter was adopted as being the most reliable. This consisted of a tube about 20 cm. long, fitted at one end with a pointer and at the other with a small eye-hole, the whole being mounted to move parallel to the edge of the cathode. The readings were done in darkness, the error being about ±0·002 cm.

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* F. W. Aston, "Experiments on the Length of the Cathode Dark Space," 'Roy. Soc. Proc.,' A, vol 79, 1907, pp. 80—95.

† *Loc. cit.*

Theory of the New Dark Space.—The preliminary measurements of "d," the length of the new dark space, showed that it was practically independent of the pressure and roughly proportional to the inverse square root of the current density. Now the equation expressing the distribution of electric force X in the Crookes dark space was shown in the previous paper* to be, under certain assumptions,

$$\mathrm{X} = (8\pi cx/\lambda)^{\frac{1}{2}},$$

where c = current density, x = distance from the edge of the Crookes dark space, and λ = velocity of a $+$ion in a unit field at prevailing pressure. If we substitute D (the length of the Crookes dark space) for x in this expression, we obtain the field just outside the cathode and, since D is roughly proportional to λ, this field is independent of the pressure and proportional to $c^{\frac{1}{2}}$, indicating that the fall of potential across d is constant.

Now suppose the electrons start from the surface of the cathode from rest, or with a uniform velocity not great enough to ionise the gas. It is clear that, if the energy necessary for such ionisation is constant, they can only attain this energy by falling through a definite potential, so that there will be a space in front of the cathode of definite length in which no ionisation will go on at all, and where no light would be expected. The new dark space may therefore be regarded as *the distance through which the electrons fall in order to attain sufficient energy to ionise the gas by collision with its molecules.*

The influence of the current density upon this phenomenon explains the fact of its being overlooked during the work on the Crookes dark space in hydrogen, since only high-current densities were then employed.

The first test of the above theory is the constancy of the fall of potential. This, by the distribution of force quoted, is $\frac{3}{2}\mathrm{V}d/\mathrm{D}\,(1-\frac{1}{4}(d/\mathrm{D})^2+\ldots)$, where V is the total fall of potential across the Crookes dark space, which, in the absence of any trace of positive column, has been shown to be practically the same as the difference of potential between the electrodes.† Since d is very much smaller than D, and the error of its measurement comparatively great, the second term may be neglected. The following tables for hydrogen and helium show that, over a large range, the fall of potential across the new dark space is constant within experimental error, and is for *hydrogen* 15 *volts, helium* 30 *volts.*

Assuming for the value of the charge on an electron $3{\cdot}4\times10^{-10}$ C.G.S., this gives for the *minimum energy required to ionise an atom of hydrogen* $1{\cdot}7\times10^{-11}$ *ergs; of helium,* $3{\cdot}4\times10^{-11}$ *ergs.* Again, taking $1{\cdot}7\times10^{7}$ as the value of e/m in electromagnetic units, *the minimum ionisation velocity is for hydrogen,* $2{\cdot}25\times10^{8}$ *cm. per second; helium,* $3{\cdot}2\times10^{8}$ *cm. per second.*

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* *Loc. cit.*

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Appearances of the New Dark Space.—Fig. 1 gives a diagrammatic section of the cathode discharge in helium at about 1 mm. pressure, with a comparatively low current density. The appearance may be broadly divided into three bands: an intensely black one of the order of 0·05 cm., the new dark space, followed by a region of moderate greenish light of length about 1 cm., the Crookes dark space, terminating finally in the brilliant bluish-green "negative glow."

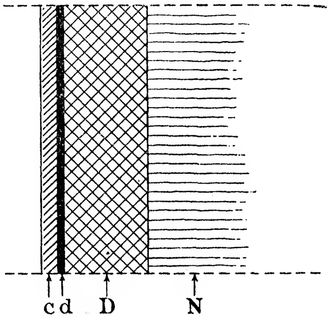

Fig. 1.

c, cathode ; *d*, new dark space ; D, Crookes dark space ; N, negative glow.

Plate 1, fig. 1, is an actual photograph of the discharge, clearly showing the relative proportions. As the camera was placed close to and level with the cathode, the curvature of the edge of the Crookes dark space is greatly exaggerated.

Plate 1, fig. 2, shows the appearance of the discharge at a very much lower current density. The Crookes dark space has lost all its distinctness of outline, while the new dark space is still sharply defined, and much larger than in fig. 1.

The theory given above is well supported by the intense blackness of the new dark space in pure helium and hydrogen, and by this theory the following effect was predicted :—

Consider the motion of the first generation of electrons starting from rest at the surface of the cathode in a field, for simplicity assumed uniform. Let d be the distance through which they must freely fall in such a field to obtain sufficient velocity to ionise the gas. If d is smaller than the mean free path of an electron under such conditions, we should expect just beyond d a maximum ionisation and a corresponding maximum light, gradually fading as we recede from the cathode and the energy of the electrons is dissipated. But, by the time a point $2d$ from the cathode is reached, the second generation of electrons, formed by collisions at d, will have attained ionisation velocity, so that there should be another, but less sharply defined, maximum of light at a point just beyond $2d$, another beyond $3d$, and so on, each getting more indistinct, so that the faint light in the Crookes dark space should be striated near the cathode. It is clear that this effect will be at its maximum when d is of the same dimensions as the mean free path of an electron under stated conditions.

Of this effect only the first maximum was observed in hydrogen, but in helium, at comparatively high pressures and very low current densities, the striation could be plainly seen and photographed. Fig. 3, Plate 1, is the reproduction of the discharge in helium at a pressure (beyond the range of the manometer) of 2 to 3 mm. With a current so small as barely to cover the surface of the cathode, the curvature of the edge of the new dark space, due to the current density not being uniformly distributed over the cathode, is clearly shown. Three distinct maxima, and traces of a fourth, could be detected on the original negative. It is interesting to note that the potential between the electrodes in this particular experiment was well below 200 volts, so that the effect can be shown with ease by means of a suitable tube and an ordinary lamp circuit.

In such striated discharges the distances between the cathode and the first maximum and between the first and second maxima, after allowances are made for the distribution of electric force, correspond to equal falls of potential as nearly as can be estimated. This conclusion is of importance, for, since the second maximum is caused presumably by electrons formed from molecules of the gas itself, their initial velocity must be negligible, therefore the initial velocity of those causing the first maximum must similarly be negligible, so that in helium the electrons may be taken as starting from an aluminium cathode at rest, and the values of minimum ionisation, energy, and velocity already evaluated for that gas become approximately absolute.

Occurrence of the New Dark Space.—It was naturally expected that this interesting phenomenon—for which the name "primary cathode dark space" has been suitably suggested—might be detected in other gases when the best conditions for its exhibition had been discovered. Up to the time of writing, however, not the slightest indication of it has been observed in air, nitrogen, oxygen, argon, or carbon monoxide. For this two explanations are naturally suggested if the theory given above is substantially correct, either—

(i) The molecules of these gases have so low an ionisation energy that "d" is too small to be detected;

(ii) The electrons liberated from the surface of aluminium by the impact

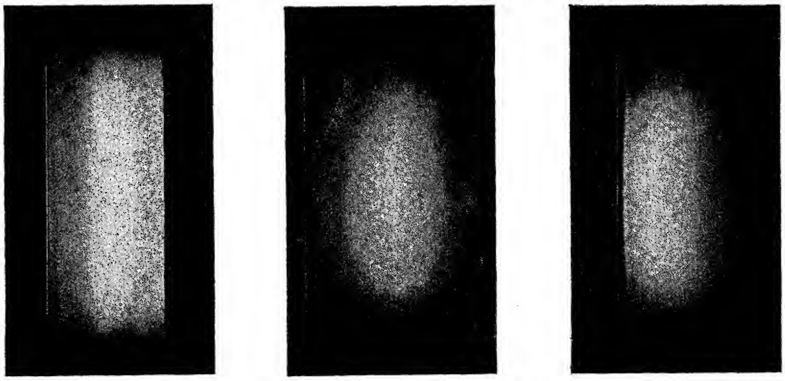

FIG. 1. FIG. 2. FIG. 3.

The white line on the left of each of the figures represents the position of the edge of the cathode.

of positive ions of these gases start with sufficient velocity to ionise at their very outset, in which case the phenomenon would not exist at all.

Some results obtained from observation of the length of *d* in mixtures of helium and oxygen, which require further investigation, show that the latter is the more probable explanation.

In conclusion, I wish to express my heartiest thanks to Professor J. H. Poynting for his kind help and encouragement throughout this research.

Table I.—Hydrogen.

V.	D.	*d*.	*d*V/D.
345	0·625	0·018	10·0
225	1·220	0·058	10·7
314	0·975	0·030	9·7
273	2·355	0·090	10·4
295	1·890	0·070	10·9
443	1·540	0·035	10·0
276	2·660	0·088	9·3
361	2·250	0·067	10·8
517	2·020	0·042	10·7
318	3·040	0·086	9·0
405	2·620	0·066	10·2
510	2·425	0·047	9·9
415	3·850	0·093	10·0
545	3·410	0·067	10·6
840	2·920	0·037	10·6

Table II.—Helium.

V.	D.	*d*.	*d*V/D.
204	0·381	0·039	20·9
202	0·496	0·051	20·8
275	0·407	0·032	21·4
200	0·610	0·061	20·0
271	0·562	0·048	20·3
200	0·887	0·087	19·6
275	0·780	0·059	20·1
325	1·010	0·064	20·5
420	1·472	0·072	20·4
590	1·422	0·047	19·5
550	1·932	0·067	19·1
730	1·762	0·048	19·5
454	2·710	0·121	20·3
530	2·499	0·098	20·7
770	3·168	0·090	21·8

V = Potential difference in volts between electrodes.
D = Length of Crookes dark space in cm.
d = Length of new dark space in cm.

The pressures range in hydrogen from 0·1 to 1·0 mm., in helium from 0·4 to 3·0 mm. Bracketed measurements were performed at the same pressure.

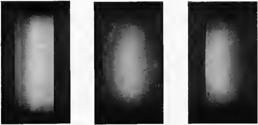

Fig. 1.

Fig. 2.

Fig. 3.

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